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HAZARDS OF LASER BEAM

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Abstract

Lasers are now indispensable tools in industry, medicine, communications, and scientific research. Their precision and efficiency have led to widespread adoption. However, their use demands significant caution, as laser radiation poses a serious hazard to the human body, especially the eyes and skin. Due to this reason, most laser sources are isolated from the environment (protective enclosure), however, there are applications where the operator is in the same airspace as the equipment emitting hazardous radiation. In an industrial environment, cutting, welding, and cleaning tasks can be performed with manual laser equipment. In this case, not only does the laser radiation pose a potential risk, but also the smoke gases and aerosols generated during the interaction between the laser light and the material, which can lead to respiratory diseases. To ensure safe operation, the proper use of protective equipment – such as laser safety goggles and specialized clothing – is crucial, along with meticulous workspace design and adherence to international standards. Ensuring radiation safety is not only essential for protecting individual health, but also a fundamental requirement for the sustainable and safe application of laser technology.

Keywords: *laser beam, scattered radiation, wavelength, handheld laser source, photon-matter interaction.*

1. Introduction

Since the first laser-emitting device was developed by Theodore Maiman at the Hughes Research Laboratory, California, in 1960, laser technologies have become indispensable in everyday life [1]. This is due to the unique properties of laser light: compared to conventional light sources, laser beams exhibit low divergence (minimal beam spread), monochromaticity (single-wavelength emission), and coherence, meaning they maintain a constant frequency and phase in their electromagnetic radiation (**Figure 1.**) [2, 3, 4]. The first two properties explain the widespread application of lasers in metrology, medicine, and the entertainment industry. However, in the field of industrial material processing, the energy distribution on the irradiated surface and the ability to achieve high power density are of paramount importance [1]. Due to these characteristics, such lasers are often referred to as high-power lasers, as they are capable of delivering power outputs in the kilowatt range [2, 3].

High-power output can be achieved using gas lasers, particularly CO_2 lasers with a gas mixture of C, N_2 and He/H_2O vapour in a 1:1:8 ratio, as well as solid-state lasers [2]. Initially, high-power laser systems were primarily developed using CO_2 la-

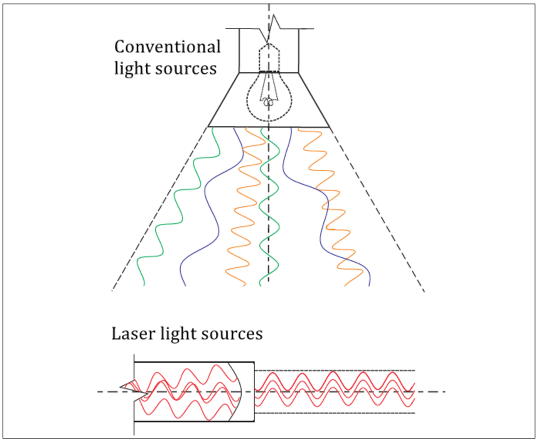

Fig. 1. *Schematic diagram of the differences between conventional and laser light sources.*

sers, but due to their complex design, operational difficulties, and high maintenance costs, their use has been declining, though they remain relevant in certain applications [1]. In this type of setup, the laser-active medium (which undergoes excitation) is the CO_2 molecule, while the additional gases or vapours are present to sustain a multilevel energy system (Figure 2). Maintaining this system is essential to achieving continuous wave (CW) laser operation, which is indispensable for cutting, surface treatment, and specific welding applications. The emitted radiation has a wavelength of 10,600 nm, which results from the vibrational energy transitions of the CO_2 molecule [2, 3].

Over the past 30 years, the development of laser technology has shifted towards solid-state lasers, particularly fiber-based excitation systems [5, 6]. One of the key reasons for this transition is that even the most robust rod lasers (an older approach) cannot compete with the size and efficiency of CO_2 laser excitation systems. Additionally, solid-state lasers offer better operational efficiency and lower running costs [7],], although their maintenance may require specialised components and tools [1]. Furthermore, the beam properties of solid-state lasers significantly expand their range of applications [2, 3].

In these laser systems, the laser medium is an optically transmissive material (crystal) that is doped with laser-active elements. The most common medium is yttrium aluminium garnet (YAG, $Y_3Al_5O_{12:}$) doped with neodymium ions (Nd^{3+}) though other dopant such as ytterbium, erbium, or holmium are also used [1, 2]. The wavelength of the emitted laser beam depends on the dopant, with neodymium-doped YAG lasers typically operating at 1064 nm (Figure 2). Lasers emitting in this near-infrared (NIR) region enable the processing of materials such as aluminium (Al), copper (Cu), and titanium (Ti), which would be challenging with CO_2 lasers [1, 2, 8].

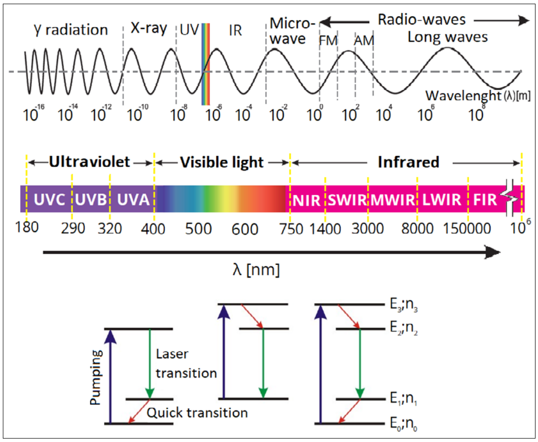

Fig. 2. *Wavelengths of radiation and schematic representation of systems with 3 or 4 energy levels*

As previously established, fiber laser technology has seen the most significant growth [8, 9], primarily due to its compact excitation system and ease of beam delivery [1, 2]. Maximising these advantages has led to the development of hand-held laser sources [5, 6, 8]. These devices are designed for multiple functions (3-in-1: cutting, welding, and surface cleaning), and upon purchase, they come with interchangeable laser heads tailored to each application. In many cases, a separate wire feeder unit is also included, ensuring a constant welding speed during filler-wire welding, as the process depends on the wire feed rate. Another factor driving the adoption of hand-held laser sources is their easy integration with collaborative robotic arms, which helps maintain a consistent welding speed in autogenous (filler-free) welding processes while improving reproducibility (Figure 3). Additionally, CNC programming enables the definition of a virtual workspace, ensuring that the system prevents laser emission outside the designated area [6].

Nowadays, fourth-generation hand-held laser systems are in production, with manufacturing primarily concentrated in the Middle East. These systems are more cost-effective than CNC-controlled industrial laser systems with fixed workspaces, with an approximate price of €10,000. However, this cost reduction often comes at the expense of compliance with stringent safety standards, as many of these devices only partially adhere to mandatory safety regulations such as EN ISO 11553-2 and CE certification. Consequently, their operation necessitates careful consideration of environmental controls and the implementation of appropriate personal protective measures [5, 6].

Fig. 3. *Hand-held laser sources (left) and their integrated system with a cobot (right)* [6]

2. Laser Classification

Laser-emitting devices are classified according to their hazard level based on the EN 60825-1 standard, with the 2014 edition currently in effect. The classification is determined by several parameters, including laser power output (*W*, mW), wavelength (nm, µm), exposure duration (s), and emission mode (continuous wave or pulsed operation) [8, 10]. There are four primary laser classes, and within certain classes, additional subcategories denoted by specific letters have been established. The "M" designation originates from the English word "magnification" and, in the context of the standard, indicates that a device originally classified as "harmless" may become hazardous if an optical instrument is placed in front of the source (Class 1M, Class 2M). The "R" designation stands for "reduced", meaning these lasers pose a lower risk compared to standard Class 3 lasers; however, they are still hazardous upon direct exposure (Class 3R). The "B" designation remains from an earlier version of the standard (Class 3B) and has no specific meaning in the current classification (in the 1994 version, Class 3A corresponded to the current Class 3R, while Class 3B remained unchanged) [11, 12, 13].

Class 1 lasers are enclosed systems and pose no risk to human health (e.g., CD players). Class 1M lasers operate at wavelengths between 302.5 and 400 nm, and while they are safe for the naked eye, they can be hazardous when viewed through optical instruments (e.g., laser pointers). Class 2 lasers (400–700 nm, max. 1 mW) rely on the blink reflex to prevent eye damage during brief exposure (e.g., laser pointers). Class 2M lasers share the same characteristics but can be harmful if viewed through optical devices (e.g., marking lasers). Class 3R lasers have an output power between 1–5 mW (400–700 nm). They are not hazardous for short exposure, but prolonged exposure can damage the eye. Warning signs (Figure 4) and protective eyewear are recommended (e.g., laser cutters). Class 3B lasers (5–500 mW) pose a risk of eye damage even from scattered radiation, making protective eyewear mandatory (e.g., industrial and medical lasers). Class 4 lasers present a severe risk of eye and skin injuries, as well as a fire hazard. Protective equipment and strict safety measures are required (e.g., industrial material processing lasers) [10, 11, 13].

Laser machine manufacturers ensure that their products comply with the strictest safety regulations. Therefore, they strive to classify their commercially available equipment within Class 1, ensuring that under normal operating conditions, these devices pose no risk to users [1, 10, 12]. It is important to note that if the safety enclosure of a device initially classified in a higher hazard category is removed (e.g., during maintenance), its actual laser classification increases, thereby posing a significant safety risk to personnel in the vicinity [5, 10].

Fig. 4. *Indications of warnings and obligations (according to ISO 7010).*

3. Biological Damages and Protection

This article aims to familiarise readers with the effects of scattered laser radiation on biological tissues. The most vulnerable organs are the eye and the skin. In all cases, accredited protective equipment must be provided in compliance with relevant laws and regulations [14].

The eye is the most sensitive organ in the human body concerning radiation exposure, making it imperative to ensure adequate protective measures during laser operations [4, 5, 10]. **Figure 5** illustrates the eye's response to different types of radiation exposure.

It can be observed that the infrared radiation (10,600 nm) emitted by CO_2 lasers is absorbed by the cornea, potentially altering its structure and the composition of the eyewater. However, under short-term exposure, these effects remain reversible [1, 12]. In the near-infrared (NIR) range, the situation is less favourable: characteristic wavelengths in this spectrum can penetrate through the lens structure, focusing the radiation onto the retina, which can result in localised coagulation [3, 4, 11]. To mitigate these hazards, specialised protective eyewear has been developed, featuring

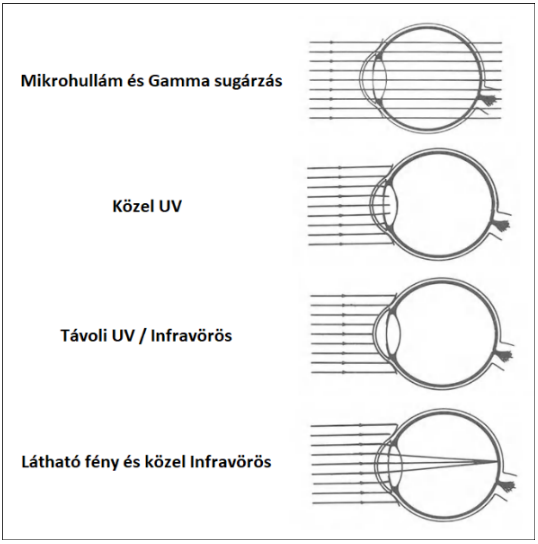

Fig. 5. *Schematic diagram of the reaction of the human eye to different radiations.*

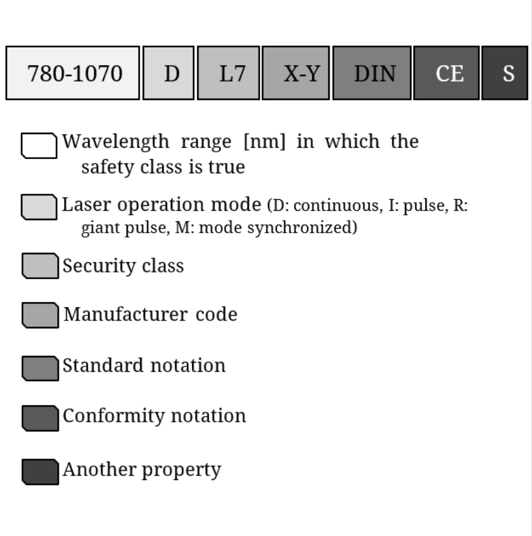

Fig. 6. *Illustrates the significant differences in the effects of various laser types.*

lenses with different refractive indices depending on the specific wavelength to be filtered. The most well-known standard for such protective products is EN 207:2020, which imposes stringent requirements, whereas its American counterpart (ANSI Z136.1) focuses solely on defining optical density values [4, 5, 6].

Optical Density (OD) indicates the effectiveness of protection against laser radiation, which is determined through various tests before protective eyewear is released to the market. The *OD* value represents the logarithmic measure of radiation attenuation, expressed as:

$$OD = \log_{10}\left(\frac{M_i}{M_t}\right), \tag{1}$$

where M_i is the power of the incident beam (W), and M_t is the power of the transmitted beam (W) [1, 4, 12]. The higher the *OD* value, the more effective the protection; however, increased OD also correlates with higher costs, making it essential to determine the minimum required protection level [12]. The relationship between OD and the Maximum Permissible Exposure (MPE; J/m^2) is given by the following equation:

$$OD = \log_{10}\left(\frac{E}{MPE}\right), \tag{2}$$

where E is the degree of exposure (J/m^2). To select the appropriate protective eyewear, it is essential to consider the operating parameters of the laser system, including wavelength, power (P; W), beam diameter (A; mm^2) and operating mode [4, 12]. The EN 207:2020 standard provides a classification table that helps determine the minimum safety rating required for protective eyewear to ensure safe usage. The technical documentation of laser safety glasses includes transmittance and optical density (*OD*) values for specific wavelengths, which should be carefully reviewed when selecting the appropriate protective equipment [5, 6, 12]. To maximise protection, shield-type eyewear should be chosen to protect the facial skin and prevent laser radiation from reaching the eyes from any angle [5, 8, 9]. The marking system for protective eyewear is illustrated in **Figure 6** [15].

Laser safety glasses can have lenses made of glass or polycarbonate. Glass lenses offer excellent light transmission properties, providing higher visible light transmission (VLT); however, they tend to be more expensive, heavier, and more fragile. In contrast, polycarbonate lenses are more cost-effective, lighter, and impact-resistant, but they allow less visible light to pass through [4]. For ergonomic considerations, the VLT value is recommended to exceed 35% [4, 5, 8].

Laser safety lenses are coated with thin layers to enhance their filtering performance. One of the most commonly used coating techniques is electron beam evaporation, where the coating material (SiO_2, HfO_2) is vaporised in a vacuum to form thin films on optical surfaces. This method is often complemented by ion-assisted deposition (IAD), which utilises an ion beam to densify the coating, reducing its porosity and enhancing laser resistance. Ion beam sputtering (IBS) offers additional advantages by producing extremely dense and low-scatter coatings (Al_2O_3, Ta_2O_5), improving laser safety glasses' durability and optical performance. Proper material selection is crucial, as optical coatings must shield against laser radiation and maintain optimal light transmission and visual comfort. Multilayer dielectric (MLD) coatings, which combine SiO_2 and HfO_2 enable protective lenses for solid-state lasers to achieve high optical density with minimal light loss. The thickness of each layer and the refractive index of the materials require precise engineering to ensure that the final coating effectively reduces hazardous reflections and maximises protection **[4, 12]**.

The human skin provides natural protection against environmental influences, but it is less effective against artificial radiation. Laser radiation at different wavelengths penetrates the skin to varying depths, leading to distinct damage mechanisms **[4, 10, 11]**. Figure 7 illustrates the significant differences in the effects of various laser types.

The CO_2 laser (10.6 μm wavelength) radiation penetrates only the uppermost layer of the skin, where it induces damage through thermal conduction. This can lead to tissue overheating and coagulation **[12]**. In contrast, solid-state lasers, which operate at an order of magnitude shorter wavelength, penetrate deeper into the skin, causing damage through the evaporation of water within the tissues and the over-excitation of haemoglobin (Fe^{2+} and Fe^{3+} ions) in the blood, leading to "blood cell explosion" **[4, 9, 11]**. This phenomenon can contribute to the formation of blood clots, which, in critical areas such as the capillaries of the eye, may cause blockages **[4, 12]**. To prevent skin injuries, the entire body must be covered with suitable protective clothing. The material must be capable of absorbing laser radiation without degrading **[5, 9, 10]**. For CO_2 lasers, conventional cowhide welding apparel provides adequate protection. However, for solid-state lasers, specialised composite fabric is required, typically incorporating stainless steel fibers (to reflect radiation) woven with absorptive textiles **[12, 16]**. The entire human body must be shielded, which is why jackets, pants, and gloves are also manufactured from such materials **[8]**. In all cases, it is essential to verify that the protective equipment provides adequate shielding for the specific laser type and power level **[4, 10]**.

4. Environmental solutions

The principle of ensuring that all laser sources are classified within Class 1 reinforces the prevention of the aforementioned injuries **[1, 10, 12]**.]. In industrial applications, high-power lasers are typically controlled by CNC systems, which confine the laser beam within a designated workspace, allowing the system to be easily enclosed and shielded from external exposure **[2, 12]**.

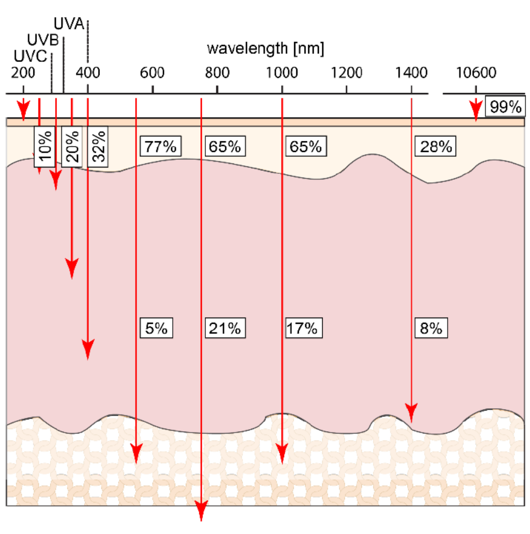

Fig. 7. *Depth of penetration of different radiations into human skin* **[15]**

Fig. 8. *Recommended personal protective equipment (internet)*

When hand-held laser sources are used, it is assumed that they are manually operated, thereby exposing the operator to significant scattered radiation [5, 6, 9]. In traditional welding techniques, workspaces are also segregated to prevent injuries caused by UV radiation to individuals outside the working area [3]. Such welding stations are typically enclosed using curtains and screens [3, 10]. However, in my opinion, this level of shielding is insufficient against NIR radiation, as these barriers do not provide hermetic isolation. Nevertheless, specialized welding screens and curtains have been developed specifically to block radiation within this wavelength range. Notably, laser-active systems are available, which are integrated with the laser source and automatically terminate photon emission upon direct radiation exposure [5, 8, 17].

If the laser system is fully enclosed, individuals outside the workspace are protected; however, within the enclosure, various materials with different orientations, absorption coefficients, and surface roughness can increase the level of scattered radiation due to diffuse reflection [4, 5, 9]. To mitigate this effect, VANTA BLACK-type coatings are commonly applied, but other solutions, such as aluminium coatings or sandwich panel structures, have also proven effective [3, 4, 12]. These latter approaches are widely used in the construction of laser welding containers. A fully enclosed welding station must feature at least one observation window, allowing individuals outside the workspace to continuously monitor the operator's health status and detect potential accidents in a timely manner [4, 18]. When selecting such windows, the same criteria applied to laser safety eye-wear must be considered [12].

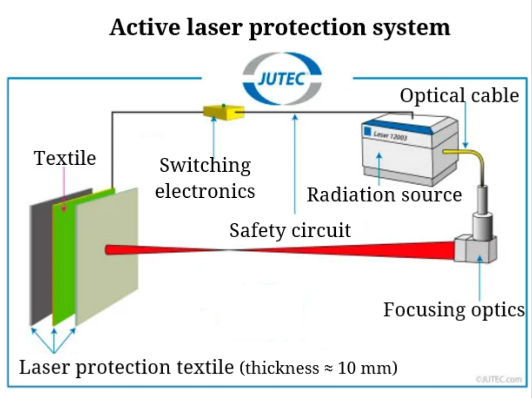

Fig. 9. *Schematic diagram of a laser-active system* [17]

Access control is of critical importance in laser work areas, necessitating the installation of clear warning signs (hazard warnings and safety obligations, Figure 4) and entry control systems. Measures such as interlocks or locked doors are recommended to prevent unauthorised access [4, 8, 18]. Other essential environmental factors include proper lighting and ventilation. During laser-based metal processing, excessive excitation of the material can generate metal vapours and other fumes, which pose serious respiratory hazards [1, 4, 10]. To mitigate these risks, complete workspace ventilation or localised exhaust systems are recommended [16, 18]. The workspace must be designed in compliance with safety protocols, and beam paths should be arranged to prevent accidental exposure. Furthermore, the operation of high-power laser systems requires the designation of a laser safety officer [4, 10, 18].

5. Conclusions

More users have turned to hand-held laser sources in recent years due to their versatile applications and low investment and operating costs. Their compact size and flexible beam delivery make them easy to handle, and they can also be integrated with collaborative robotic arms, enhancing productivity and process automation [2, 5, 6]. Despite their affordability and versatility, hand-held lasers present significant safety challenges, as operators are directly exposed to scattered laser radiation [4, 10, 11]. To ensure adequate protection, the workspace must be enclosed with appropriate materials, and LEAN principles should be considered during its design [1, 12, 16]. The safe use of hand-held lasers requires not only appropriate personal protective equipment—such as specialised eye-wear and protective clothing—but also a well-structured work environment. This includes access control, hazard labelling, warning systems, and adequate ventilation to remove generated fumes and vapours [4, 10, 18].

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